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Structural Design Methodologies for Ceramic-Based Material Systems

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Summary

One of the primary pacing items for realizing the full potential of ceramic-based structural components is the development of new design methods and protocols. This article focuses on the low-temperature, fast-fracture analysis of monolithic, whisker-toughened, laminated, and woven ceramic composites. A number of design models and criteria are highlighted. Public domain computer algorithms, which aid engineers in predicting the fast-fracture reliability of structural components, are mentioned. Emphasis is not placed on evaluating the models but instead is focused on the issues relevant to the current state of the art.

Introduction

Structural ceramic components are being considered for a broad range of practical applications. Motivation has emerged from innovative high-technology industries that include aerospace, automotive, energy production, and microelectronics. As a result, current computational structural mechanics methods have to evolve to keep pace with these new technology initiatives. Noor (ref. 46) points out that developments in this field of mechanics are driven by the need for improved productivity and cost-effective systems. He also notes that one of the primary pacing items is the prediction and analysis of failure in structural components manufactured from new materials. Thus, realizing the full potential of ceramic-based materials requires the development of advanced structural analysis technologies, some of which are highlighted in this report. Specifically, the objective is to touch upon key design requirements peculiar to this material, with the intent of increasing the design engineer's awareness and confidence in using ceramic components. The focus of this discussion is aimed primarily at low-temperature (<1000 °C), short-term failure analysis of monolithic, whisker-toughened, laminated, and woven ceramic composites. From this viewpoint we can consider the mechanical behavior of this material to be linear elastic. Hence, little attention (with the exception of woven composites, where fiber architecture plays a key role) is given to the development of models that predict global stiffness properties. Much of the report details the use of stochastic models that account for uncertainties associated with the variation in material strength. Several test-bed software programs are mentioned that incorporate these stochastic models, are user friendly, handle data efficiently, and have architectures that allow users to add features with minimal difficulty.

The advantages of ceramic structural components (both monolithic and composite) include high strength, high stiffness, and good creep and corrosion resistance. All of these traits are maintained even when components are placed in applications involving very high service temperatures. These properties provide the potential for greatly increasing fuel efficiency in aerospace and automotive engine applications, as well as for surpassing anticipated stringent emissions standards in automotive systems. Considering that ceramics will be produced from abundant nonstrategic materials, it is not surprising that research has focused on improving ceramic material properties through processing as well as on establishing protocols for sound design methodology. The emerging ceramics, particularly silicon nitride and silicon carbide, have the potential for competing with metals in many demanding applications. Unfortunately, ceramics also have several inherent undesirable properties that must be considered in the design procedure. The most deleterious of these are low strain tolerance, low fracture toughness, and a large variation in failure strength observed in monolithic materials. Under applied load, large stress concentrations occur at microscopic flaws, which are unavoidably present as a result of processing or in-service environmental factors. The observed scatter in component strength is caused by the variation in size and orientation of these flaws, which leads to sudden catastrophic crack growth when the crack driving force or energy release rate reaches a critical value. In addition, most ceramics exhibit decreasing bulk strength with increasing component volume (the so-called size effect).

Analyzing components fabricated from ceramic materials requires a departure from the usual deterministic design philosophy (i.e., the factor-of-safety approach) prevalent in designing metallic structural components, which are more tolerant of flaws. Since failure is governed by the scatter in strength, statistical design approaches must be employed. Fractographic examination of failure surfaces indicates that the critical flaws causing failure can be put into two general categories: defects internal or intrinsic to the material volume (volume flaws), and defects extrinsic to the material volume (surface flaws). Intrinsic defects are a result of processing. Extrinsic flaws can result from grinding or other finishing operations, from chemical reaction with the environment, or from the internal defects intersecting the external surface. The different physical nature of these flaws results in dissimilar failure response to identical loading situations. Consequently, separate criteria must be employed to describe the effects of the applied loads on the component surface and volume.

In view of the limitations of monolithic ceramics, it is not surprising that the genesis of structural ceramics has included the addition of a reinforcing second phase. Adding a second ceramic phase with an optimized interface improves fracture toughness, decreases the sensitivity of the brittle matrix to the aforementioned microscopic flaws, and even improves strength. It has been demonstrated experimentally that dispersing whiskers in a brittle matrix will mitigate crack growth. The presence of whiskers near the crack tip modifies fracture behavior by effectively increasing the required crack driving force through several mechanisms. These mechanisms include crack deflection, crack pinning, whisker bridging, and whisker pullout. In addition, lowered creep rates and varied success in improving resistance to thermal shock have been reported. Whisker reinforcement may also be combined with other toughening mechanisms, such as continuous fiber reinforcement, which results in a material system known as a hybrid composite, or employment of a matrix material capable of undergoing stress-induced transformation toughening. In addition to capturing the inherent scatter in strength, the reliability analysis of components fabricated from composite ceramics must account for material symmetry imposed by the reinforcement. For example, the whisker orientations encountered in hot-pressed and injection-molded whisker-toughened ceramics usually impart a locally transversely isotropic material symmetry. Whether the second phase imparts an orthotropic, transversely isotropic, or isotropic material symmetry, structural reliability models must account for material orientation in a rational manner.

For aerospace components (specifically those of the national aerospace plane, the space shuttle main engine, and advanced heat engines), ceramic prototypes have already demonstrated functional capabilities at temperatures approaching 1400 °C, which is well beyond the operational limits of most metallic materials. Furthermore, composite ceramics (e.g., continuous fiber, laminated, and woven ceramics) offer significant potential for raising the thrust-to-weight ratio of gas turbine engines by tailoring directions of high specific reliability. In general, continuous ceramic fiber composites exhibit an increase in fracture toughness, which allows for "graceful" rather than catastrophic failure. When loaded in the fiber direction these composites retain substantial strength capacity beyond the initiation of transverse matrix cracking although neither constituent would exhibit such behavior if tested alone. Indeed, first matrix cracking consistently occurs at strains greater than that in the monolithic matrix material. As additional load is applied beyond first matrix cracking, the matrix tends to break in a series of cracks bridged by the ceramic fibers. Additional load is borne increasingly by the fibers until the ultimate strength of the composite is reached. For most applications the design failure stress will be taken to coincide with the first-matrix-cracking stress. The reason for this is that matrix cracking usually indicates a loss of component integrity and allows high-temperature oxidation of the fibers, which leads to embrittlement of the composite.

The ongoing metamorphosis of ceramic material systems and the lack of standardized design data have tended to minimize the emphasis on modeling. Many structural components fabricated from ceramic materials were designed by "trial and error," since emphasis was placed on demonstrating feasibility rather than fully understanding the processes controlling behavior. This is understandable during periods of rapid improvement in material properties for any system. Current research combines experimental investigation of failure mechanisms with the development of failure models. This facilitates improvements in processing and allows one to gain insight and intuition before constructing multiaxial failure theories that in some respect reflect the appropriate microstructural behavior. Most models for ceramic composites focus on mode I fracture behavior, although some models are amenable to multiaxial load conditions. Many of the modeling techniques have been adapted from existing technologies in other material systems. In this article several phenomenological, semiempirical, fracture mechanics, and statistical models are briefly highlighted. Public domain computer algorithms that, when coupled with a general-purpose finite element program, predict the fast-fracture reliability of a structural component under multiaxial loading conditions are mentioned. Here the emphasis is not on evaluating the models in detail. More complete discussions are available elsewhere. We simply wish to call attention to issues relevant to the current state of the art.

Methodologies for Monolithic Ceramics

Traditional analyses of component failure usually employ deterministic approaches where failure is assumed to occur when some allowable stress level or equivalent stress is exceeded. The most widely used of these theories are the maximum normal stress, maximum normal strain, maximum shear stress, and maximum distortional energy criteria of failure. These phenomenological theories have been reasonably successful in predicting the onset of yield failure in ductile materials. However, for the reasons mentioned in the introduction, these deterministic techniques are not relevant to monolithic ceramic component design. The first probabilistic approach that accounted for the scatter in fracture strength and the size effect in brittle materials was introduced by Weibull (refs. 57 to 59). This approach is based on the previously developed weakest link theory (WLT) attributed to Midgley and Pierce (refs. 25, 37, and 44) who originally proposed it while testing yarn. The weakest link theory is analogous to pulling a chain, where catastrophic failure occurs when the weakest link in the chain is broken. Unlike Pierce, who assumed a Gaussian distribution of strength, Weibull assumed a unique probability density function that bears his name. To extend the approach to multiaxial states of stress, Weibull proposed calculating a quantity, referred to as "the risk of rupture," by averaging the tensile normal stress in all directions. Although this approach is intuitively plausible, it is somewhat arbitrary. It lacks a closed-form solution and therefore requires computationally intensive numerical modeling. Barnett et al. (ref. 3), and Freudenthal (ref. 26) proposed an alternative approach, usually referred to as "the principle of independent action" (PIA), for finding the failure probability due to multiaxial stress fields. This principle states that the survival probability of a uniformly stressed material element in a multiaxial stress state equals the product of the survival probabilities for each principal stress applied individually. Qualitatively, the PIA theory is equivalent in a probabilistic sense to the maximum stress failure theory. The Weibull method of averaging the tensile normal stress over the unit sphere (about all possible directions), and the PIA model have been widely applied in brittle material design (refs. 16, 20, 41, 48, and 60).

However, the Weibull and PIA hypotheses do not specify the nature of the defect-causing failure. Attempts to experimentally verifiy the polyaxial predictions of these theories have been inconclusive. Subsequently, the accuracy of these theories has been questioned, and other statistical models have been proposed whose basis is founded in fracture mechanics. Griffith (refs. 28 and 29) proposed a fracture theory for linear elastic brittle materials where failure was due to the presence of cracks of specified size and shape distributed randomly throughout the material. He originally assumed that no interaction takes place between adjacent cracks and that failure occurs at the flaw with the least favorable orientation relative to the far-field stress. The Griffith energy balance criterion for fracture states that crack growth will occur if the energy release rate reaches a critical value. Griffith's theory provides a sound physical basis for describing the rupture process in an isotropic brittle continuum. However, it does not allow for the scatter in strength, since crack size and orientation are not treated as probabilistic quantities. The concepts developed by Batdorf and Crose (ref. 5) are important in that they represent the first attempt at extending fracture mechanics to reliability analysis in a consistent and rational manner. By describing material volume and surface imperfections as randomly oriented noninteracting discontinuities (cracks) with an assumed regular geometry, they explicitly treated the mode I and mode II (even mode III if appropriate) contributions to the fracture process. They assumed that mixed-mode or unimodal failure occurs when the effective stress, which is a combination of normal and shear stresses, on the weakest flaw reaches a critical level. The effective stress is a function of the assumed crack configuration, the existing stress state, and the fracture criterion employed. Accounting for the presence of shear on the crack plane reduces the normal stress needed for fracture and yields a more accurate reliability analysis. However, Batdorf's first approach only considers coplanar crack extension. Several criteria have been subsequently proposed, such as Shetty's work (ref. 52), that account for out-of-plane crack growth under mixed-mode load conditions.

These statistical failure theories can be readily integrated with the finite element methods of structural analysis. Component integrity is computed by calculating element-by-element reliability, since each element can be made arbitrarily small so that the element stress gradient is negligible. According to the weakest link concept, the component survivability is simply the product of the individual element reliabilities. A public domain computer program that is coupled with several general-purpose finite element codes has been developed at the NASA Lewis Research Center to perform this type of reliability analysis. CARES (Ceramics Analysis and Reliability Evaluation of Structures, refs. 30, 31, and 47) is an integrated computer program that couples elastostatic analysis output from either the MSC/NASTRAN or ANSYS finite element codes with two-parameter Weibull and Batdorf fracture statistics to predict the fast-fracture reliability of monolithic ceramic components. CARES has two primary functions: (1) estimation of the Weibull shape and scale parameters and the Batdorf crack density coefficient from the fracture data of simple uniaxial tensile or flexural specimens, and (2) fast-fracture reliability evaluation for a finite element model of a ceramic component under mechanical or thermal loading or both. Data analysis and reliability evaluation are performed as a function of temperature and surface area or

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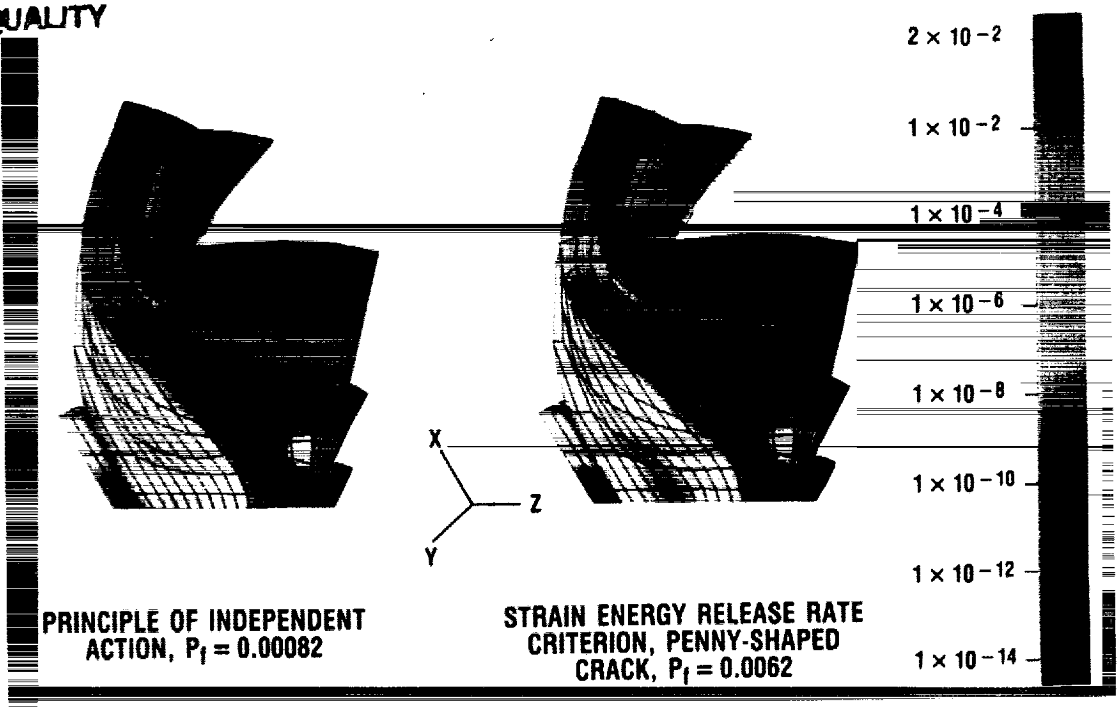

(a) Principle of independent action; probability of failure, 0.00082.
(b) Strain energy release rate criterion for penny-shaped crack; probability of failure, 0.0062.

Figure 1.—Comparison of risk-of-rupture intensities for volume flaw analysis using principle of independent action (PIA) and strain energy release criterion.

volume or both. Material parameter calculations are independent of finite element output. Component reliability for volume flaws is determined from element stress, temperature, and volume calculations are independent of finite element output. Component reliability for volume flaws is determined from element stress, temperature, and volume output by using isoparametric three-dimensional or axisymmetric elements. Reliability for surface flaws is calculated from isoparametric shell element stress, temperature, and area data. For example, CARES has been used for the preliminary design of silicon nitride mixed-flow rotors, which have applications in small, high-temperature engines. Making use of cyclic symmetry, we analyzed a single blade and a section of the rotor hub; the risk-of-rupture intensities along with the component probability of failure are presented in figure 1. Note that the risk-of-rupture intensity is independent of individual element geometry and provides the design engineer with a means of identifying critical regions of the component. The analysis was performed by using two of the available design options, the PIA criterion and the strain energy release rate criterion.

Methodologies for Whisker-Toughened Ceramics

As a result of the strong hybrid ionic-covalent bonds in monolithic ceramics, these materials suffer from low strain to failure and low fracture toughness. One of the initial approaches taken for improving the mechanical performance of ceramics is adding a second phase. The assumption is that proper tailoring of the composite microstructure will dramatically improve the mechanical properties. This ongoing effort has included the dispersion of whiskers and particle reinforcements. Conceptually, one hopes that adding a second phase will perturb the stress field near the tip of a critical crack so as to reduce the stress intensity. Lange (ref. 39) originally proposed a method for computing the stress necessary to propagate a crack front that bows between two obstacles and developed a modified Griffith equation where the increase in fracture surface energy is directly related to a line tension effect. The approach assumes that the whiskers have a higher fracture toughness than the matrix and that the crack front penetrates the matrix material in a nonlinear fashion (i.e., "bows out"). The postulated behavior is analogous to the motion of dislocations through a precipitate-hardened material. Evans (ref. 21) and Green (ref. 27) have suggested modifications to this model that account for whisker morphologies. Toughening by crack deflection arises from the crack front tilting or twisting or both as it encounters the second phase. This produces noncoplanar crack extension and a lower stress intensity at the crack tip. The direction taken by the crack front after deflection is controlled by whisker morphology and the residual stress field (e.g., tensile or compressive). A fracture mechanics model for crack deflection that accounts for mixed-mode behavior has been proposed by Faber and Evans (ref. 23). Angelini and Becher (ref. 1) have presented evidence from electron microscopy observations that indicates whiskers may bridge the crack as it propagates. From these data Becher and coworkers (ref. 6) developed a model for predicting the increase in fracture toughness due to the closure stresses imposed on the crack by the bridging whiskers. Finally, Wetherhold (ref. 61) developed a model based on probabilistic principles that enables the computation of an increased energy absorption during fracture due to whisker pullout. However, in contrast to continuous-fiber-reinforced ceramics (discussed in the next section), whisker pullout is limited by the short lengths of the whiskers (typically less than 100 μm).

The primary intent of these models is to consider the composite as a structure and develop predictive methods for optimizing the microstructure. Ultimately, these concepts would be used to similarly refine the design of structural components. Whenever practical, elegant design methods incorporate the relevant physics of failure into the analysis of a component's macroscopic response. However, at this point obstacles arise that prevent taking this approach in analyzing components manufactured from whisker-toughened ceramics. First, the crack mitigation processes strongly interact, and it is difficult to experimentally detect or analytically predict the sequence of mechanisms leading to failure. Furthermore, with the exception of the model by Faber and Evans, the methods mentioned previously consider only mode I failure. This precludes conducting a structural analysis on a component subject to multiaxial states of stress. Finally, these initial analytical techniques have focused primarily on predicting behavior by using deterministic approaches. Even though improved processing techniques have resulted in the reduction of inhomogeneities, uniform whisker distributions, and dense matrices, failure remains a stochastic process for discrete particle-toughened materials.

The Weibull modulus is a good measure for quantifying variability in failure strength. For this class of ceramic composite, Claussen and Petzow (ref. 13) have cited the Weibull modulus of 24. Even at this level the variability is still too high for the application of deterministic strength theories. An alternative approach that conveniently sidesteps the aforementioned obstacles is to compute reliability in terms of macrovariables by using phenomenological criteria. Focusing a design approach at the macroscopic level represents a philosophical drawback, for it excludes any consideration of the microstructural events that involve interactions between individual whiskers and the matrix. This point of view implies that the material element under consideration is small enough to be homogeneous in stress and temperature yet large enough to contain a sufficient number of whiskers so that the element is a statistically homogeneous continuum. Obviously, these conditions cannot always be met for they depend on characteristic component dimensions, the severity of gradients within the component, and the relative size of the material microstructure. However, when these conditions are satisfied, multiaxial reliability models can be systematically formulated under the assumption that the material is homogeneous and has stochastic properties and behavior that can be deduced from well-chosen phenomenological experiments. From a historical perspective the phenomenological approaches are usually (but not always) supplanted by techniques that accurately reflect the physics of the microstructure. Precedence for this can be found in modeling monolithic ceramics, where the detailed concepts of Batdorf have for the most part superseded phenomenological approaches such as the PIA model.

Duffy et al. (ref. 17) presented the details of using phenomenological approaches in designing whisker-toughened ceramic components. Depending on its fabrication a whisker-toughened composite may have isotropic, transversely isotropic, or orthotropic material symmetry. The principle of independent action might be an appropriate first approximation of phenomenological theory for isotropic whisker composites. Duffy and Arnold (ref. 18) presented a noninteractive phenomenological model for whisker-toughened composites with a transversely isotropic material symmetry often encountered in hot-pressed and injection-molded whisker-toughened ceramics. In their discussion they adopted the viewpoint that reliability is governed by weakest link theory and assumed the existence of a failure function per unit volume, where the unit volume was considered to be an individual link. If the failure of the individual links were considered to be statistical events (assumed to be independent), then through an appropriate volume integration of this function an overall component reliability could be computed. This approach required the specification of a unit vector that identified a local material orientation. The material orientation was defined as the normal to the plane of isotropy, and the dependence of the failure function accommodated this orientation. The stress and the local preferred direction were allowed to vary from point to point, so that the stress field and the unit vector field had to be specified to define the failure function. Since the scalar-valued failure function was dependent on second-order tensors, the form of the function had to remain invariant under proper orthogonal transformations. This required the function to be insensitive to the global coordinate system used to define the stress tensor and material directions. Through the use of invariant theory, a finite set of invariants, known as an integrity basis, was defined. The invariants of the integrity basis can be likened to a basis vector that helps to span a particular vector space (e.g., the set of unit vectors that span the Cartesian space). A slightly different set of invariants that correspond to physical mechanisms related to failure was constructed from the integrity basis. These invariants can be identified with a principal stress or a component of the stress tractions coincident with a material direction. For orthotropic composites the failure function must also reflect the appropriate material symmetry. This requires two orthogonal vectors to identify local material orientation, and Duffy and Manderscheid (ref. 19) have proposed a model for whisker-toughened ceramics with orthotropic material symmetry.

The phenomenological reliability models mentioned previously have been incorporated into a test-bed software program given the acronym TCARES (Toughened Ceramics

Analysis and Reliability Evaluation of Structures, see ref. 17). This is a public domain computer algorithm and is a direct offspring of the CARES algorithm mentioned previously. When coupled with a general-purpose finite element program, the algorithm enables the design engineer to predict the fast-fracture reliability of a structural component under multiaxial load conditions.

Methodologies for Continuous-Fiber-Reinforced Ceramic Composites

Although whisker-toughened ceramics have enhanced toughness and reliability, they do not substantially lessen the possibility of catastrophic failure, a problem that restricts their use in certain applications. Continuous-fiber-reinforced ceramic composites, however, can provide significant increases in fracture toughness along with ability to fail in a non-catastrophic manner (often referred to as "graceful" failure). Prewo and Brennan (refs. 7, 49, and 50) have demonstrated that incorporating fibers with high strength and stiffness into brittle matrices with similar coefficients of thermal expansion yields ceramic composites with the potential of meeting high-temperature performance requirements. Typical stress-strain curves of unidirectional systems are bilinear when loaded along the fiber direction, with a distinct breakpoint that usually corresponds to transverse matrix cracking. Since monolithic ceramics are much stronger in compression than in tension, fibers are incorporated to mitigate tensile failure by bridging inherent matrix flaws. Yet one should be mindful that the failure characteristics of these composites are controlled by a number of local phenomena including matrix cracking, debonding and slipping between matrix and fibers, delamination, and fiber breakage. Relative to design issues, the current state of the art focuses on unidirectional composites. At present most research is concerned with predicting composite tensile strength in the fiber direction, which addresses the upper bound problem. Conversely, a tensile load applied transverse to the fiber direction results in failure behavior similar to that of a monolithic ceramic, which represents the lower bound of composite strength. For this reason (and since most structural applications involve multiaxial states of stress) practical continuous-fiber composites are reinforced in two or three directions by using laminate, woven, or braided architectures. Eventually, angle-ply laminate response must be understood and new failure modes (e.g., delamination) must be admitted to design protocols. This will occur as processing techniques for these composite systems develop and mature. However, since current analytical research efforts have concentrated on predicting the tensile strength of unidirectional composites, attention is given to this system in the remainder of the section. Methods for analyzing laminated ceramic composite systems are slowly emerging, and mature design concepts are limited. Hence, laminates are not discussed, and woven composites are mentioned in the next section.

The various design methods mentioned here can be grouped into categories entitled "phenomenological," "fracture mechanics," and "statistical." With the exception of the last category the analytical design concepts are deterministic, predicting failure by using single-valued strength parameters. A number of theories exist that treat unidirectional composites as homogenized, anisotropic materials. These phenomenological criteria are familiar to design engineers experienced in dealing with polymer matrix composites. The Tsai-Wu (ref. 55) model is the most notable, and the reader is encouraged to study two excellent reviews of phenomenological failure models by Labossiere and Neale (ref. 38), and Nahas (ref. 45) for a broad treatment of this subject. We touch upon these criteria for completeness and note that they can accommodate multiaxial states of stress. However, they are deterministic, and for those primarily concerned with predicting tensile strength in the fiber direction, other models based on the principles of fracture mechanics are available.

Specifically, the early fracture mechanics approaches for predicting strength were concerned with the occurrence of first matrix cracking due to tensile loads in the fiber direction. The first model was proposed by Aveston, Cooper, and Kelly (ACK) (ref. 2). The model, postulated on the basis of energy principles, assumes a purely frictional bond between the matrix and the fiber. This allows for significant slipping at the interface. Application of an energy balance approach leads to an expression for the strain corresponding to first matrix cracking. This expression includes the matrix fracture surface energy, the stiffness and volume fractions of the matrix and the fiber, the interfacial shear strength, and the fiber diameter. Whereas the ACK model simply considers the change in energy before and after crack propagation, the more rigorous analysis of Budiansky, Hutchinson, and Evans (BHE) (ref. 8) considers a propagating crack. The analysis considers the change in potential energy with respect to crack growth, which is essentially the Griffith energy criterion. The model was developed for a general class of fracture problems known as steady-state cracking and includes the combined effects of friction and normal residual stress at the interface. Usually, the two limiting cases of unbonded frictionally constrained fibers and initially bonded fibers subject to residual stresses are considered. The results of the initial case (i.e., the large fiber slip condition) can be generalized to the ACK model. The second case of an initially bonded interface that debonds as the crack tip approaches the fiber assumes that the lost integrity of the bond is permanent. Shear stresses are not allowed to develop in the debonded region downstream from the crack tip. Marshall, Cox, and Evans (MCE) (ref. 42) have derived a model based on a stress intensity factor approach and consider the transition from notch-insensitive, large-crack behavior to notch-sensitive, short-crack response. This consideration was not taken into account in the previous two models. However, the MCE model falls short in providing consistent modeling parameters. McCartney (ref. 43) has suggested corrections to the MCE model and provides valuable new insights relating to the computation of a threshold stress, below which matrix cracking is impossible regardless of the size of the preexisting defect.

Another model based on the principles of fracture mechanics has been proposed by Ballarini and Ahmed (ref. 4). This approach utilizes a local-global model (i.e., a combination of microstructural and macrostructural analyses) that considers the vicinity of a crack tip to be a process zone. This zone is embedded in an anisotropic continuum that is then modeled by conventional finite element methods. The local heterogeneous zone (or region) consists of the fibers, the matrix, and the fiber-matrix interface and is represented by a succession of spring elements. This allows the region to behave as an anisotropic continuum, subject to the condition of plane strain. Each spring stiffness corresponds to the elastic properties of the materials they represent. It is assumed that each material has a predetermined critical rupture energy, and that the springs are released in the order that these critical values are attained, permitting the crack to propagate in a noncoplanar fashion. The local zone is embedded in the global region by enforcing displacement compatibility at the nodes common to the local elements and the global isoparametric elements.

Recently, experimental results have clearly indicated that the fiber-matrix interface plays a key role in determining the strain to failure and toughness of this material system. Control of interface behavior essentially determines the load transfer between the fiber and the matrix. Composites with high toughness but relatively low matrix strain to failure exhibit extensive debonding at the interface. This is accompanied by substantial pullout of the fibers from the matrix. Composites with low toughness but excellent matrix strain to failure fail owing to the propagation of a single near-planar crack that passes through the matrix and the fiber (i.e., the composite behaves as though it were a monolithic ceramic). Therefore, before mechanical models can be developed and evaluated and composite behavior can be empirically correlated with the properties of fiber-matrix interfaces, the fundamental properties of these interfaces must be fully understood. Evans and his coworkers have intensively investigated and evaluated the debonding properties of various unidirectional ceramic composites (ref. 54 is typical of their work). Charlambides and Evans(ref. 10) proposed a model that predicts the trends in interface debonding during fiber pullout for composites with the interface subject to residual tension. The results provide the knowledge needed to assess the role of debonding. Evans et al. (ref. 22) use basic mechanics to analyze both initial debonding along interfaces and the kinking of interface cracks into a fiber. The results indicate that debonding requires less than about one-fourth of the interface fracture energy required for the fiber. Furthermore, they have shown that, when this condition is met, fiber failure does not normally occur by deflection of the debond through the fiber. Instead, fiber failure is governed by weakest-link statistics.

The criteria discussed so far have all been deterministic. Some phenomenological and mechanistic models are amenable to stochastic formulations. We note that there is a great deal of intrinsic variability in the strength of each brittle constituent of a ceramic matrix composite but, depending on the composite system, the matrix cracking strength may be deterministic or probabilistic. However, the ultimate unidirectional composite strength will always be probabilistic, since its value is determined by the strength distribution of the brittle fiber. Thus, statistical models are required for those composite systems that possess a great deal of scatter in the initiation of first matrix cracking or have linear stress-strain curves to ultimate failure. The criteria of Sun and Yamada (ref. 53) and Cassenti (ref. 9) are based on statistical design methods that make use of available distributions of experimental strength data. These are quite similar to the methods proposed by Duffy and Arnold mentioned in the preceding section, and indeed both can be shown to be special cases of the previously cited work. Three stochastic models, described by Jayatilaka (ref. 32), for the ultimate unidirectional strength of a composite are based on the variation in fiber strength. For composites with high fiber volume fractions, the most conservative model is predicated on bundle theory, an analytical approach discussed in detail by Daniels (ref. 15). The method is applicable when the cumulative fiber strength is adequate to carry the load after matrix failure. The other two models discussed by Jayatilaka are less conservative and applicable to the behavior of polymer matrix composites.

Methodologies for Fabric-Reinforced Ceramic Matrix Composites

Advancements in textile weaving technology have resulted in significant new opportunities for utilizing high-performance two- and three-dimensional fabric-reinforced ceramic matrix composites in high-temperature structural applications (see Fareed et al. (ref. 24) and Ko et al. (ref. 34)). Attractive features include improvements in damage tolerance and reliability, flexibility in fiber placement and fabric architecture, and the capability of near-net-shape fabrication. This latter feature is of particular interest, since applications where these materials can have a significant effect often require complex geometric shapes. However, designing structural components that are fabricated from materials incorporating ceramic fiber architectures also represents new and distinct challenges in analysis and characterization. Preforms, which serve as the composite skeleton, are produced by weaving, knitting, and braiding techniques (see ref. 36). Woven fabrics (i.e., two-dimensional configurations) exhibit good stability in the mutually orthogonal warp and fill directions. Triaxially woven fabrics, made from three sets of yarns that interlace at 60 ° angles, offer nearly isotropic behavior and higher in-plane shearing stiffness. A three-dimensional fabric, consisting of three or more yarn diameters in the thickness direction, is a network in which yarns pass from fabric surface to fabric surface. These three-dimensional systems can assume complex shapes and provide good transverse shear strength, impact resistance, and through-the-thickness tensile strength. Furthermore, the problem of interlaminar failure is totally eliminated.

Complex textile configurations and complicated yarn/matrix interface behavior represent a challenge in determining the properties of these composites. Considerable effort has been devoted to evaluating the effectiveness of various reinforcement architectures based on approximate geometrical idealizations. Chou and Yang (ref. 11) have summarized the results of extensive studies in modeling thermoelastic behavior of woven two-dimensional fabrics and braided three-dimensional configurations. They proposed a unique method of constructing structure-performance maps, an example of which is shown in figure 2. The relative effectiveness of various textile reinforcing schemes can be assessed by using these maps. In the future as these materials emerge, the maps should serve as a guide for design engineers wishing to specify these materials.

Several analytical models have been developed to predict the mechanical properties and structural behavior of these composites. The approaches are based on modified laminate theory, a geometric unit cell concept, or both. For two-dimensional woven-fabric-reinforced composites, Chou and Ishikawa (ref. 12) have proposed three models based on laminate theory. These models are known as the mosaic, crimp, and bridging models. The mosaic model ignores fiber continuity and treats a fabric composite as an assemblage of cross-ply laminates. The crimp model takes into account the continuity and undulation of the yarns; however, it is only suitable for plain weaves. The bridging model, developed for satin weaves, is essentially an extension of the crimp model. This model takes into consideration the contribution to the total stiffness of the linear and nonlinear yarn segments.

The concept of a geometric unit cell has been widely used to characterize the complex structure of three-dimensional fiber-reinforced composites and to establish the constitutive relations. In general, this approach assumes that the thermoelastic properties are functions of fiber spatial orientation, fiber volume fraction, and braiding parameters. Ma et al. (ref. 40) developed a fiber interlock model that assumes the yarns in a unit cell of a three-dimensional braided composite consist of rods which form a parallelepiped. Contribution to the overall strain energy from yarn axial tension, bending, and lateral

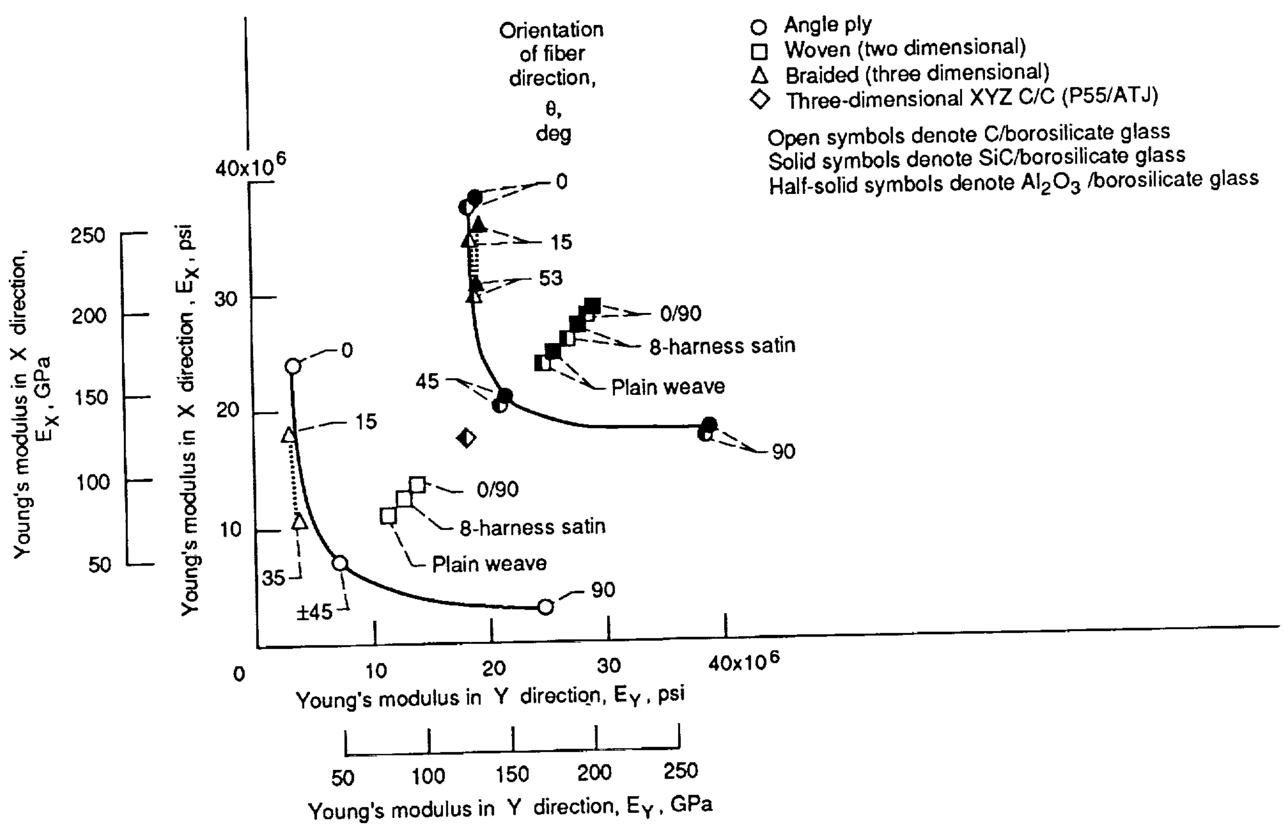

Figure 2.—Structural performance map for carbon/borosilicate, SiC/borosilicate, and Al_2O_3/borosilicate glass composites. (Adapted from ref. 11)

compression are considered and formulated within the unit cell. Yang et al. (ref. 62) proposed a fiber inclination model that assumes an inclined lamina is represented by a single set of diagonal yarns within a unit cell. Ko et al. (ref. 35) have also proposed a unit cell model where the stiffness of a three-dimensional braided composite is considered to be the sum of the stiffnesses of all its laminae. The unique feature of this model is its ability to handle three-dimensional braid as well as the other multidirectional reinforcements, including five-, six-, and seven-directional yarns that are either straight or curvilinear. Finally, Crane and Camponeschi (ref. 14) have modeled a multidimensional braided composite by using modified laminate theory. This approach determines the extensional stiffness in the three principal geometric directions of a braided composite. We note that these analytical models are based on previous research related to polymeric and metal matrix composites. Although much of the current modeling effort is in its infancy, the aforementioned approaches have demonstrated merit relative to experimental data. However, caution is advised, since agreement between model predictions and experimental data is subject to interpretation. Yet accurate predictions of mechanical properties are a necessity when conducting stress-strain analyses, which logically precede all failure studies.

Predicting the onset of failure represents a complex task because of the numerous failure modes encountered in this class of materials. As research progresses, deterministic and probabilistic schools of thought will emerge. For either case, models based on the principles of fracture mechanics as well as phenomenological models will be proposed. It is expected that deterministic approaches will precede the development of probabilistic concepts. Initial research regarding failure analysis for whisker-toughened and long-fiber ceramic composites typically borrowed concepts from polymer and metal matrix composite research. We anticipate a similar trend with woven composites. For example, the work of Yang (ref. 63) and the previously cited work of Chou and Ishikawa have proposed techniques for predicting the onset of short-term failure in fabric-reinforced polymer composites that make use of the maximum stress and maximum strain failure criteria. The work by Walker et al.(ref. 56) represents another potential concept that could be used. Here mesomechanics is employed to predict the behavior of metal matrix composites. This approach takes advantage of the periodic nature of the microstructure and homogenizes the material through volume-averaging techniques. In Walker's work a damage parameter can be included as a state variable in formulating constitutive relationships. Other suitable failure concepts may emerge from the field of continuum damage mechanics as well.

Currently, phenomenological approaches may be the logical first choice owing to the complexity of the microstructure. Yet it should be realized that random microcracks and voids are present in woven ceramics. These microdefects may lead to statistically distributed failures and failure modes. However, at this time failure models based on probabilistic concepts have not been proposed. Furthermore, the evolution of the microstructure in response to a hostile thermomechanical environment must be studied in order to provide rational design protocols for materials with tailored fiber architectures. Experiments are needed to identify the underlying mechanisms of failure, and innovative experimental techniques must accompany the development of constitutive models that incorporate damage evolution at the microstructural level. The task will be iterative, requiring constant refinement of correlations between physical mechanism and mathematical description. As processing methods improve, it is likely that the popularity of fabric-reinforced ceramic matrix composites will increase. Fiber preform design, constitutive modeling, and material processing will require the combined talents and efforts of material scientists and structural engineers.

Future Directions

Ceramic material systems will play a significant role in future high-temperature applications. To this end, a number of issues must be addressed by the structural mechanics research community. We begin by pointing out that recent progress in processing ceramic material systems has not been matched by mechanical testing efforts. There is a definite need for experiments that support the development of reliability models. Initially this effort should include experiments that test the fundamental concepts embedded in the framework of current stochastic models. As an example, probing experiments could be conducted along various biaxial load paths to establish level surfaces of reliability in a particular two-dimensional stress space (similar to probing yield surfaces in metals). One could then verify such concepts as the maximum stress response, which is often assumed in the multiaxial reliability models proposed for these materials. After a theoretical framework had been established, characterization tests would then be conducted to provide the functional dependence of model parameters with respect to temperature and environment. Finally, data from structural tests that are multiaxial in nature (and possibly nonisothermal) would be used to challenge the predictive capabilities of models through comparison with prototypical response data. These tests involve inhomogeneous fields of stress, deformation, and temperature and would include two-bar tests as well as plate and shell structures. Results from structural testing provide feedback for subsequent modification. Ad hoc models result in the absence of structured interaction between the experimentalist and the theoretician. The validity of these models is then forever open to question. Furthermore, we cannot overemphasize that this genre of testing supports the development of methods for designing components, not for designing the material. Currently, this effort is hampered by the quality and scarcity of data. Ceramic properties pertinent to structural design, which include stochastic parameters, vary with the test methods. The mechanics research community is beginning to realize this, and a consensus is beginning to form regarding the adoption of standards. However, we wish to underscore the fundamental need for experimental programs that are relevant to structural mechanics issues.

Although the discussion in previous sections focused on time-independent analyses, using ceramics as structural components in harsh service environments requires thoughtful consideration of reliability degradation due to time-dependent phenomena. This issue finds relevance in the design of monolithic and composite ceramic components. For monolithic ceramics (and perhaps whisker-toughened ceramics), mechanisms such as subcritical crack growth, creep rupture, and stress corrosion must be dealt with. Computational strategies are needed that extend current methods of analysis involving subcritical crack growth and creep rupture to multiaxial states of stress. Furthermore, the bulk of current literature dealing with stress corrosion highlights experimental observations, with little attention given to failure analysis. Several authors have suggested dealing with this mechanism analytically through the use of chemical reaction rate theory. Indeed, this approach would be a good starting point, since it deals with the chemistry of failure at the microstructural level. However, the development of current methods for predicting the service life of ceramics is hampered by the lack of data on the behavior in various environments of interest.

Large strides have been made in understanding crack growth behavior in monolithic and whisker-toughened ceramics. However, one important aspect that has not been addressed in detail is the effect of rising *R*-curve behavior. Clearly, brittle materials need to be toughened, and this is often accomplished by creating a process zone around the crack tip. Within this zone localized energy dissipation takes place and results in the development of damage tolerance through an increasing resistance to crack growth with crack extension. Under these conditions fracture toughness becomes functionally dependent on crack size. Failure of materials exhibiting *R*-curve behavior would depend not on the initial distribution and orientation of flaw sizes but on the rate at which resistance increases with crack growth. Several authors have discussed in theoretical terms the effect that *R*-curve behavior has on the stochastic parameters that are necessary for short-term failure as well as on life prediction (ref. 33). Again, little data exist that correlate strength distribution to this behavior. Furthermore, if ceramic materials mimic ductile failure locally, cyclic fatigue may become a design issue. Under cyclic loads the process zone advances as the crack tip extends, and brittle fracture mechanics may need to be modified to account for pseudo-ductile fracture (ref. 51). Hence, application of modified metallic fatigue analyses may be a distinct possibility.

Careful thought is also required in defining structural failure in woven ceramics and long-fiber laminated ceramics. Current research initiatives have focused on the analysis of first matrix cracking and ultimate strength (in the fiber direction) of an individual lamina. These analyses must be extended to multi-axial states of stress, and failure in an angle-ply lamina must be dealt with effectively. In a laminate these types of failure mechanisms effectively reduce the stiffness of the failed ply. Reduced stiffness causes local redistribution of the load to adjacent layers. In addition, delamination between laminae will relax the constraining effects among layers and allow in-plane strains to vary in steps within a laminate. These effects require the development of rational load redistribution schemes. Failure analysis of woven ceramics must initially deal with quantifying damage induced by service loads in the absence of a discernible macrocrack. Here phenomenological approaches such as continuum damage mechanics would offer the most promise. Furthermore, issues germane to component life such as cyclic fatigue and creep behavior must also be addressed analytically and experimentally for both types of composites.

In closing, we recognize that when failure is less sensitive to imperfections in the material, stochastic methods may not be that essential. Yet trends in design protocols are moving in the direction of probabilistic analyses (even for metals) and away from the simplistic safety factor approach. In this sense brittle ceramics will serve as prototypical materials in the study and development of reliability models that will act as the basis of future design codes.

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16. Abstract

One of the primary pacing items for realizing the full potential of ceramic-based structural components is the development of new design methods and protocols. This article focuses on the low-temperature, fast-fracture analysis of monolithic, whisker-toughened, laminated, and woven ceramic composites. A number of design models and criteria are highlighted. Public domain computer algorithms, which aid engineers in predicting the fast-fracture reliability of structural components, are mentioned. Emphasis is not placed on evaluating the models but instead is focused on the issues relevant to the current state of the art.

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